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Evaluating benefits of low-cost household digesters for rural Andean communities

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ABSTRACT

Low-cost household digesters are a promising appropriate technology which can help reducing the pressure on the environment due to deforestation and greenhouse gases emissions. The biogas and biofertilizer produced can alleviate poverty, by improving health conditions, increasing crops productivity and saving working time and burden for women and children. The aim of this study is to evaluate low-cost digesters technical, environmental and socio-economic impacts in rural communities of the Peruvian Andes, where a pilot project was developed during the last 3 years. Although the benefits are restricted by the performance of anaerobic digestion at high altitude, the results show that the digesters improve household living conditions and economy, while reducing environmental impacts. Biogas production covers around 60% of fuel needs for cooking, leading to 50–60% decrease in firewood consumption (i.e. deforestation) and greenhouse gases emissions; the annual income is increased by 3–5.5% due to fertilizer savings and potato sales. These values could be improved by enhancing digesters performance and the sustainability of the technology.

Contents

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1. Introduction

During the last decade there has been a greater concern than ever for sustainable development, which is changing the way international development aid is provided [1]. As expressed by the Millennium Development Goals, the aim is to make aid more effective in supporting progress and meeting the needs of the poor [1]. International development agencies stated that the guiding principles behind a new policy for successful development cooperation include [1–3]: (i) ownership by developing countries of their own development process; (ii) increased attention and priority to the social dimension and poverty reduction; (iii) ensuring sustainability of effect. To improve the chances of success, attention needs to be placed on some of the common areas of weakness in programmes and projects. Three main areas are identified consistently [3]: (i) planning and project formulation; (ii) stakeholders involvement; (iii) monitoring and evaluating programmes and projects.

This paper is focused on the evaluation of a project. By definition, evaluation aims to make an assessment, as systematic and objective as possible, of an ongoing or completed project, programme or policy [2]. Generally, evaluation tries to determine the relevance and fulfilment of objectives, developmental efficiency, effectiveness, impact and sustainability. Evaluation, like monitoring, can apply to many things, including an activity, project, programme, strategy, policy, topic, theme, sector or organization.

The project evaluated in this study deals with the implementation of low-cost household digesters in rural communities of the Peruvian Andes. A low-cost household digester is a "modern" appropriate technology to improve the traditional energy use of biomass resources in developing countries [4], where 28% of the population lack access to electricity and 56% still rely on solid fuels, traditional biomass and coal [5]. Apart from capturing methane, a greenhouse gas (GHG) 21 times more powerful than carbon dioxide, household digesters are also believed to provide social and economic benefits, like poverty alleviation, indoors environment improvement, crop productivity increase, workload reduction for women and children [5–10].

Up to date, only a few studies have been carried out to assess household digesters advantages. Arthur et al. [5] presented the status of biogas technology and its potential benefits in Ghana. Their qualitative analysis showed that the benefits (e.g.: environmental sustainability, improved health, increase in agricultural productivity) could be significant; although financial activities and subsidies should be introduced at the initial stage. Yu et al. [11] estimated the environmental benefits of small scale household digesters in rural China, by determining GHG emissions reduction. The study highlighted that biogas, as a renewable clean fuel, had reduced 45.59×10^6 $t_{CO_{2eq}}$ year^{-1} from 1991 to 2005 in rural China. Bhattacharya and Salam [12] compared the GHG emission factor of biogas combustion to that of firewood, agriculture residue and charcoal in Asian countries. This study showed that the emissions generated by using firewood and improved cookstoves are around 8 times higher than biogas. Van Groenendaal and Gehua [10] carried out a survey to assess the increase of family's income in rural China thanks to the digester implementation, by evaluating the reduction of expenditure on fuels and fertilizer. This study suggested that low-cost household digesters are mainly seen as a renewable energy technology, and that its benefits as a technology to produce fertilizer are insufficiently appreciated. Katuwal and Bohara [8] carried out a survey in rural communities of Nepal, concluding that family-size digesters considerably improve households living quality, because they reduce the firewood consumption by 54% and save 1.56 h day^{-1} on firewood collection.

In this context, systematic studies which quantify altogether technical, environmental and socio-economic benefits of household digesters are still missing. Moreover, most of the studies have been carried out in Asian countries, where socio-economic conditions are different from Latin America, and where brick masonry digesters have been mainly implemented. The adaptation of low-cost tubular digesters to the Andes is a new issue that dates back only 4 years ago [13–15]. For this reason, the quantification of technical, social, economic and environmental impacts in rural households is of great interest for Non-Governmental Organizations (NGOs) and other aid and financial entities.

The aim of this study is to assess and quantify technical, environmental and socio-economic benefits of low-cost household tubular digesters implemented in rural communities of the Peruvian Andes. To this end, during 2009–2010, 12 digesters where monitored and their benefits quantified.

2. Project description and evaluation

2.1. Project description

In the Department of Cajamarca, located at the Northern region of the Peruvian Andes, around 50% of the population lives in rural areas [16], with an economy based on self sufficient agriculture and farming. The main crops are potatoes and sweet corn, while the main livestock are cows, guinea pigs and llamas. In most cases, there is still a lack of basic services such as potable water or electricity. Biomass consumption, including firewood and air-dried cattle dung, accounts for 65–75% of the total fuel consumption for cooking [16]. Improved cookstoves or smoke control systems are generally missing, generating indoor air pollution (especially particulate matter) and unhealthy environments [17,18].

In 2007 local and international NGOs (Practical Action from Peru, Engineers without Borders from Spain and Green Empowerment from USA) together with research institutions (Technical University of Catalonia) started a pilot project dealing with the implementation of low-cost tubular digesters adapted to Andean Plateau [13]. The project involved 12 households in rural communities of Cajamarca, located at 3300 m a.s.l. At the same time, a pilot plant was implemented and monitored in the National Institute for Agricultural Innovation (INIA) (Cajamarca) with the aim of characterizing digesters operation and biogas production at high altitude [13,19].

The main purpose of the project was to improve the living quality of rural families, by providing a clean fuel which can substitute traditional biomass. The project also aimed to: preserve the environment by reducing GHG emissions and deforestation; decrease family's expenses for fuel or fertilizer; and reduce the workload and time spent by women and children for wood collection. Beneficiaries belonged to associations already involved in previous projects of the involved NGOs. They had to meet the following criteria: low income, availability of cattle dung and lack of improved cookstoves. Beneficiaries and technical staff collaborated during biogas systems implementation. Local organizations also organized workshops to build the capacity of stakeholders for the implementation, management and maintenance of the technology. The pilot project was completely financed by development aid funds and the cost of each biogas plant (including the PVC tubular bag, biogas storage and cook-stove) was estimated around \$400 per family.

2.2. Project evaluation

Evaluation science is very wide and there are a number of tools that can be used to assess a project. Due to the scarcity of resources and logistics, the method used in this study is "planned vs. actual", which aims to analyze the achievement of the objectives established in a project [2]. The simplicity of this method allows transferring evaluation results to all stakeholders ensuring a participatory approach. It consists of comparing what was

Table 1
Pilot project objectives and assessment indicators.

Objectives	Indicators		Unit
Technical			
Providing clean fuel to meet family's needs for cooking	I1	Coverage of fuel needs for cooking	m^3_{biogas} day^{-1}; %
Environmental			
GHG emissions reduction	I2	CO_{2eq} emissions reduction	$t_{CO_2 eq}$ $year^{-1}$ per family; %
Deforestation reduction	I3	Firewood consumption reduction	t_{wood} $year^{-1}$ per family; %
Indoor environment improvement	I4	Harmful gases emissions from biogas (CO, H_2S, SO_2)	ppm; %
	I5	Harmful emissions from firewood (PM)	%
Economic			
Decreasing family's expenses for fuel and fertilizer	I6	Family's income saved thanks to biogas and biofertilizer supply	$$year^{-1}$ per family; %
Increasing crop yields	I8	Income increase due to potatoes sale	$$year^{-1}$ per family; %
Social			
Decreasing time for firewood collection	I8	Hours for firewood collection reduction	h $week^{-1}$ per family; %
Health improvement	I9	People died due to chronic obstructive pulmonary disease	n_{people} $year^{-1}$; %

Table 2
Summary of the main results of the questionnaire.

Information	Options	Percentage of families (%)
Technical		
Fuel used for cooking in previous scenario	Firewood	100
Time spent for cooking	3 h day^{-1}	70
	3.5 h day^{-1}	30
Coverage of fuel needs for cooking with biogas	<25%	14
	25–75%	43
	>75%	43
Environmental		
Firewood consumption reduction	<25%	0
	25–75%	71
	>75%	29
Economic		
Family's income	Around $180 $month^{-1}$	72
	Around $360 $month^{-1}$	28
Family's expenses for fuel	0 (obtain fuel for free)	100
Family's expenses for fertilizer in previous scenario	<$35 $year^{-1}$	43
	>$35 $year^{-1}$	57
Social		
Time spent for firewood collection reduction	<25%	14
	25–75%	72
	>75%	14

originally planned with what actually happens. Calculating indicators as percentages and ratios is a particularly useful way of presenting performance information. Indicators must be derived from project objectives.

Table 1 summarizes the objectives and indicators measured in this project. They represent digesters benefits to rural households in Cajamarca. The project objectives were defined during project formulation among the NGOs and stakeholders involved. Unfortunately, the health indicator (I9) could not be considered, because it should be assessed during the impact assessment, 5–10 years after the project is terminated [2].

Table 3
Summary of digester's benefits.

Indicators/benefits		Quantification	Comparison with previous scenario
Technical			
I1	Coverage of fuel needs for cooking	0.53 m^3_{biogas} day^{-1}	Biogas covers around 60% of the fuel need for cooking
Environmental			
I2	CO_{2eq} emissions reduction	2703.97 $kg_{CO_{2eq}}$ $year^{-1}$ per family	CO_{2eq} emissions decrease by 50%
I3	Firewood consumption reduction	1.88 t $year^{-1}$ per family	Firewood consumption decrease by 53%
I4	Harmful gases emissions from biogas (CO, H_2S, SO_2)	Not detected	No emissions were determined
I5	Harmful emissions from firewood (particulate matter)	–	Particulate matter emissions reduction by 60%
Economic			
I6	Family's income saved with biogas and biofertilizer	$46 $year^{-1}$ per family	Annual income increase due to fertilizer saving and potato sale around 3–5.5%
I7	Family's income increase due to potatoes sale	$75 $year^{-1}$ per family	
Social			
I8	Time spent for firewood collection reduction	2.5 h $week^{-1}$	Time spent for firewood collection decrease by 50%

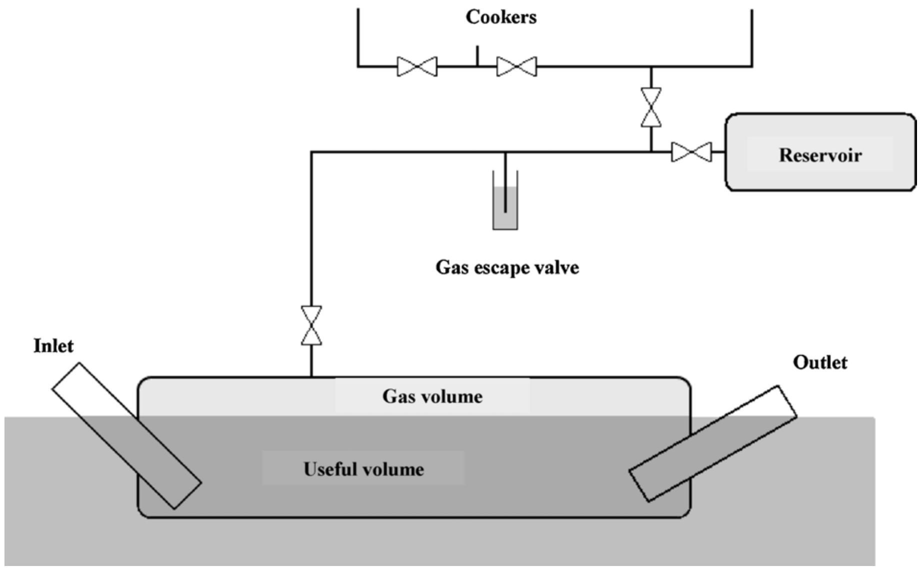

Fig. 1. Schematic of the systems: plug flow tubular digester with biogas reservoir and biogas cookstove.

The next sections describe the methodology used and results obtained for each indicator. This information was collected by means of a questionnaire carried out by sociologists and technical staff to the 12 rural families involved in the project. The questionnaire aimed at obtaining the following information: (i) technical aspects (i.e. type of fuel used for cooking and time spent cooking with biogas or other fuels); (ii) environmental aspects (i.e. number of cows per family, quantity of firewood used for cooking); (iii) economic aspects (i.e. family's income and expenses for fuel and fertilizer); (iv) social aspects (i.e. time for wood collection, type of crops). The results of the questionnaire and evaluation are summarized in Tables 2 and 3.

3. Technical benefits

The digesters implemented in the Department of Cajamarca are adapted to the conditions of the Adean Plateu (Fig. 1) [13]. In such plug-flow reactors, the wastewater flows through a tubular polyethylene or PVC bag (the reactor) from the inlet to the outlet, while biogas is collected by means of a gas pipe connected to a reservoir. There is neither heating nor mixing. The tubular plastic bag is buried in a trench and covered with a greenhouse, in order to increase process temperature and minimise overnight temperature fluctuations. Recently, the dome greenhouse design has been spreading because of its easiness of handling [19]. A pipeline transports biogas from the digester to the kitchen or cooking area; in this way the gas can be used directly as a heat source, replacing wood or LPG for cooking or heating. Table 4 summarizes the main operational and design parameters of low-cost tubular digesters implemented in Cajamarca.

Table 4
Digesters design and operational parameters.

Parameter	Value
Digester design and material	Plug flow tubular PVC
Temperature range (°C)	Psychrophilic (<25)
Total and useful volume (m^3)	10 and 7.5
Hydraulic residence time (days)	90
Substrate (% total solids)	Cow manure (3–5)
Organic loading rate ($kg_{VS}\ m^{-3}\ day^{-1}$)	0.22
Feeding pattern	Semi-continuous

Adapted from Ferrer et al. [13].

Table 5
Average values of biogas production and composition.

Parameter	Value
Biogas production ($m^3_{biogas}\ day^{-1}$)	0.53 ± 0.01
Specific biogas production ($m^3_{biogas}\ kg^{-1}_{SV}$)	0.32 ± 0.09
Carbon dioxide (% CO_2)	40 ± 1.8
Hydrogen sulphide (% H_2S)	0.11 ± 0.01
Methane (% CH_4)	≥60

Adapted from Ferrer et al. [13].

Like mentioned above, one of the main purposes of the pilot project is to provide a clean fuel to substitute firewood, used by 30% of the total Peruvian population [16]. In tropical countries household digesters can provide biogas in such quantity that it can be used even to generate electricity [20]. However, in the Andean Plateau, the main objective is to satisfy family's needs of fuel for cooking. The digesters are implemented at household scale instead of community scale due to cultural and socio-economic conditions in the area [21]. They are designed according to the number of cows per family.

Coverage of fuel needs for cooking was evaluated by measuring biogas production and comparing it with the fuel demand, according to family's needs. As mentioned in Section 2.1, previous studies carried out in a pilot plant defined biogas production and composition, and operational parameters. Tables 5 and 6 summarize digesters technical performance [13].

The results of the technical evaluation showed that, generally, the families cook during 3 h day^{-1}, while current biogas production (0.53 $m^3_{biogas}\ day^{-1}$) ensures about 2 h day^{-1}. It means that biogas

Table 6
Average feedstock and effluent characteristics.

Parameter	Unit	Feedstock	Effluent
pH		8.82 ± 0.39	7.14 ± 0.11
CE	($\mu S\ cm^{-1}$)	17.35 ± 7.27	8.00 ± 0.90
TS	(%)	25.96 ± 4.73	0.70 ± 0.08
VS	(% TS)	67.61 ± 2.44	44.22 ± 5.13
TKN	(% TS)	0.21 ± 0.01	0.05 ± 0.01
N-NH_4	(% TS)	0.02 ± 0.02	0.03 ± 0.01
P-P_2O_5	(% TS)	0.10 ± 0.03	0.03 ± 0.01
K-K_2O	(% TS)	0.37 ± 0.09	0.09 ± 0.05

Adapted from Ferrer et al. [13].

covers around 60% of the fuel needs for cooking and families continue to use firewood to cover the total fuel requirement. In other countries, like China, India or Costa Rica, the biogas generated in household digesters meets all cooking fuel needs; sometimes it is even used for lighting, breeding, heating water or electricity generation [20,22–25]. The extreme climate conditions (i.e. low temperature and pressure) of the Andes constitute a limiting factor for anaerobic digestion [26]. In this context higher biogas production could be obtained by increasing digesters volume; however this might be restricted by the number of cows per family and it would always increase implementation costs.

Despite the hard weather conditions in Andean communities, household digesters are able to provide a considerable amount of clean fuel. Nevertheless, future studies should be aimed at improving digesters performance at high altitude.

4. Environmental benefits

4.1. GHG emissions reduction

Firewood is one of the main sources of GHG emissions in rural areas [27]; therefore its substitution with biogas can lead to important GHG emissions reduction.

The method used to quantify GHG emissions reduction was proposed by the Integrated Pollution Prevention and Control (IPPC) and The Gold Standards [28]. It has already been applied by Yu et al. [11] to small scale household digesters in rural China. This method takes into account GHG emissions reduction from energy substitution (ERES), GHG emissions reduction from manure management (ERMM) and GHG emissions resulting from biogas combustion (EBC). The amount of reduced GHG emissions is estimated in terms of CO_2 equivalents (CO_{2eq}) according to the global warming potential (GWP) of CH_4 (23) and N_2O (296), in the horizon of 100 years [29].

ERES represents the amount of a given fuel type that is substituted by biogas. It is determined by the following formula [28]:

$$\mathrm{ERES}_{\mathrm{GHG;fuel}} = \mathrm{FS}_{\mathrm{fuel}} \cdot \mathrm{EF}_{\mathrm{GHG;fuel}} \tag{1}$$

where $\mathrm{ERES}_{\mathrm{GHG;fuel}}$ stands for the emissions of a given GHG by the type of fuel substituted with biogas (t); $\mathrm{FS}_{\mathrm{fuel}}$ is the amount of fuel substituted with biogas (t); and $\mathrm{EF}_{\mathrm{GHG;fuel}}$ is the emission factor of a given GHG by the type of fuel ($\mathrm{kg\,t^{-1}}$).

The default $\mathrm{EF}_{\mathrm{GHG;fuel}}$ for the combustion of different fuels is reported by the IPCC guidelines [28]. In this study the only fuel considered is firewood. To determine the quantity of firewood ($\mathrm{FS}_{\mathrm{wood}}$) substituted with biogas, a survey to beneficiaries was conducted. We considered CO_2 ($\mathrm{EF}_{\mathrm{CO_2;wood}} = 1450\,\mathrm{kg_{CO_2}\,t_{wood}^{-1}}$), CH_4 ($\mathrm{EF}_{\mathrm{CH_4;wood}} = 2.7\,\mathrm{kg_{CO_2}\,t_{wood}^{-1}}$) and NO_2 ($\mathrm{EF}_{\mathrm{CO_2;wood}} = 0.06\ \mathrm{kg_{CO_2}\,t_{wood}^{-1}}$) emissions for ERES determination.

ERMM was estimated by the following formula [28]:

$$\mathrm{ERMM} = \mathrm{EF_T} \cdot N_{\mathrm{T}} \tag{2}$$

where ERMM stands for the GHG emissions reduction due to the manure digestion, as opposed to storage. $\mathrm{EF_T}$ is the emission factor for the defined animal population ($\mathrm{kg_{CH_4}\,head^{-1}\,year^{-1}}$); N_{T} is the number of heads of livestock species T per household with digester; and T is the category of animal.

In this study ERMM was determined from CH_4 emissions, and the animal category is cow. Each family has 3 cows ($N_{\mathrm{T}} = 3$), which only stay in sheds overnight. Therefore, a correction factor of 25% should be considered [30]. The emission factor in this case is $\mathrm{EF_{cow}} = 1\,\mathrm{kg_{CH_4}\,head^{-1}\,year^{-1}}$ [28].

EBC is determined by the following formula [11]:

$$\mathrm{EBC} = \mathrm{BC} \cdot \mathrm{EF_{GHG}} \tag{3}$$

where BC represents biogas consumption (t) and $\mathrm{EF_{GHG}}$ is the GHG emission factor for biogas combustion. The amount of biogas consumption in this case is $0.525\,\mathrm{m^3\,day^{-1}}$ per family (Table 5) or $0.23\,\mathrm{t\,year^{-1}}$; and biogas density is $1.22\,\mathrm{kg\,m^{-3}}$ [31]. In this study we considered CO_2 ($\mathrm{EF}_{\mathrm{CO_2;biogas}} = 748\,\mathrm{kg_{CO_2}\,t_{biogas}^{-1}}$) and CH_4 ($\mathrm{EF}_{\mathrm{CH_4;biogas}} = 0.02\,\mathrm{kg_{CO_2}\,t_{biogas}^{-1}}$) emissions.

The total emissions reduction (NET) expressed in $\mathrm{kg_{CO_{2eq}}}$ is estimated by the following formula:

$$\mathrm{NET} = \mathrm{ERES} + \mathrm{ERMM} - \mathrm{EBC} \tag{4}$$

The results of the survey showed that firewood reduction accounts for $1.88\,\mathrm{t\,year^{-1}}$. In this case, ERES, ERMM and EBC are 2863.21, 15.75 and 174.98 $\mathrm{kg_{CO_{2eq}}\,year^{-1}}$ per family, respectively. NET accounts for 2703.97 $\mathrm{kg_{CO_{2eq}}\,year^{-1}}$ per family. In the previous scenario, without digester, GHG emissions were around 5448.04 $\mathrm{kg_{CO_{2eq}}\,year^{-1}}$; consequently GHG emissions reduction is estimated around 50%. Notice that with more favourable weather conditions GHG emissions reduction can arise $4500\,\mathrm{kg_{CO_{2eq}}\,year^{-1}}$ per family [8].

From a regional perspective, in the Department of Cajamarca there are around 200,780 small farmers [16]. The implementation of low-cost digesters would then reduce by 2% the national GHG emissions due to agriculture, which are estimated around $24.83 \times 10^9\,\mathrm{kg_{CO_{2eq}}\,year^{-1}}$ [32].

Nowadays global warming and climate change are issues of a great concern [33]; low-cost household digesters are a promising solution to reduce GHG emissions in Andean communities, even if environmental benefits are more significant when biogas production fully satisfies family's needs for cooking, or in large scale projects [11].

4.2. Deforestation reduction

Biogas also helps improving environmental conditions by conserving forests [8]. In the Department of Cajamarca, excessive exploitation of forest wood has prompted deforestation. Only in 2005, 520,030 ha of forest were deforested and the trend is increasing [34]; firewood being one of the major causes of deforestation. The amount of firewood saved in each household was quantified during the questionnaire.

With current biogas production ($0.53\,\mathrm{m^3_{biogas}\,day^{-1}}$), firewood consumption reduction is about $1.88\,\mathrm{t\,year^{-1}}$ per family, accounting for 53% of the total quantity of firewood used before digesters implementation. In valley region of Nepal, family-size digesters implementation has reduced the consumption of firewood by $3\,\mathrm{t\,year^{-1}}$ [8] due to a better performance of the biogas system. Thus, the improvement of the technology would also contribute in reducing deforestation. In the Peruvian Andes, digesters spreading could decrease environmental impacts due to deforestation, like elevation of river levels, and subjection of downstream villages and agricultural fields to flooding, which characterizes Peruvian Andes especially during the rainy season [35].

4.3. Indoor emissions

In rural zones of Peru only 10% of the population use improved cookstoves [16,36]. Firewood and air-dried cattle dung are used for cooking in most households. The use of traditional fuels produces obnoxious smoke and particulate that pollute the kitchen and causes several respiratory diseases [8]. In Peru around 1000 of people die every year due to chronic obstructive pulmonary disease attributed to solid fuel use [36]. The most harmful gases produced by firewood combustion are particulate matter (PM), CO, CO_2, SO_x, NO_x [12].

Table 7
Detectable values and exposure limit values of CO, H_2S and SO_2.

Parameter	Value	Exposure limit values	
		Value	References
CO (ppm)	<20[a]	50 (8-h time-weighted)	[37]
H_2S (ppm)	<2[a]	10 (1-h-exposure)	[38]
SO_2 (ppm)	<10[a]	177 (10-min mean)	[39]

[a] Below detection limit.

The digesters provide a clean fuel that helps reducing indoor air pollution and incidence of respiratory diseases. Biogas combustion does not produce PM emissions; however the H_2S content is a major concern.

In order to assess the threat of biogas emissions, colorimetric tubes (Gastec, 2.1D, 2.4D, 2.5DH) were used in the pilot plant, to measure CO, SO_2 and H_2S indoor emissions resulting from biogas combustion in cookstoves, during 5 h of cooking. The experiment was repeated 4 times. Besides, PM emissions reduction was determined qualitatively, considering the reduction of time spent cooking with firewood.

According to the results, the value of CO, SO_2 and H_2S indoor emissions were always below detection limits and the limits proposed by the Occupational Safety and Health Administration (OSHA) and the World Health Organization (WHO) [37–39] (Table 7). Therefore, cooking with biogas does not generate harmful gases emissions in indoor environment. During 1 h day^{-1} the families still use firewood without improved cookstove. Consequently, PM emissions have been reduced by 60%. Where biogas covers the total fuel needs, smoke reduction in the kitchen is drastic, and so are eyes infections and respiratory diseases reduction [8,40]. In this case, even if indoor environment improvement is limited by a partial replacement of fuel, all families stated that the use of biogas had improved indoor environment, hence the living quality of women and children. The use of improved cookstove [41] or solar cookstoves during the day [42] should be implemented together with biogas systems to reduce PM emissions completely.

5. Economic benefits

5.1. Families' expenses for fuel and fertilizer

Digesters provide both biogas which is used for cooking and an effluent that can be used as fertilizer [10]. The questionnaire helped determining the type and cost of fuel employed for cooking as well as families' expenses for fertilizer in the previous scenario. These data are compared to the current scenario.

The results showed that in the previous scenario the families involved in the pilot project only used firewood, which nowadays is for free. Families' income is around \$180–360 $month^{-1}$. Some beneficiaries use compost, which costs around \$46 per year. This amount can be saved using digester's effluent as fertilizer, representing about 1–2% of families annual income.

5.2. Increase of crop yield

It is believed that digesters effluent can have a positive effect on crop production, giving economic benefits to self sufficient agriculture [8,10]. However, there are no studies that characterize the potential of low-cost tubular digesters effluent as a fertilizer in Andean rural areas.

For this reason, a preliminary study was carried out in order to analyze the potential of digesters effluent as a fertilizer in potato (*Solanum tuberosum*), the most common crop in Cajamarca. Three treatments were compared: the digester effluent (biofertilizer) (T1), compost (T2) and a control without fertilization (T3). Three replicates of each treatment were randomly distributed; each replicate with 15 plants. The amount of biofertilizer (T1) and compost (T2) was determined based on a total application of 50 kg of nitrogen per hectare [43]. The potato yield per hectare was the measured parameter. The results showed that T1, T2 and T3 have an average yield of 25.27, 22.82 and 19.82 t ha^{-1}, respectively.

We hypothesize that in the scenario preceding digesters implementation, the total potato production is intended to family's self consumption. This means that the surplus production obtained using the biofertilizer can be sold. The income due to potato sales was quantified by means of a questionnaire.

The survey showed that, generally, rural families grow 0.125 ha of potatoes, with 2 harvests per year. The surplus production of potatoes with biofertilizer compared to compost is 0.6 t $year^{-1}$ per family. The average potatoes price is about \$125 t^{-1}. Therefore, the family's income could increase by \$75 $year^{-1}$, corresponding to an increase of annual family income by 2–3.4%. This is significant for rural families whose economy is based on self sufficient agriculture and farming. However, the digester is still costly for poor families who are excluded from subsidies. This aspect was also shown by Van Groenendaal and Gehua [10]. They carried out a survey for users and nonusers in three villages of western China; observing that the effects of digesters use on the family economy are often small.

Costs and financing are important barriers to digesters spreading at high altitude. Up to date, digesters implementation at high altitude is neither affordable nor sustainable for rural households. Further studies should be developed aiming at: (i) reducing digester costs; (ii) generating employment by creating local cooperatives for biogas systems installation and maintenance; (iii) assessing the capacity to pay by families; (iv) evaluating carbon emissions trading or other sustainable subsidies mechanism.

6. Social benefits

6.1. Time for wood collection

Social impacts associated with household fuel use in poor countries include risk of injury and violence (primarily to women) while collecting wood and other solid fuels, and missed time from school for children [36]. The time spent collecting solid fuel also imposes opportunity costs that constrain socio-economic development. Using a questionnaire it was possible to quantify the time spent for wood collection.

The information provided by the survey highlights that only women and children are responsible for firewood collection. The time spent is around 5 h $week^{-1}$. Due to digesters implementation, this time is reduced by 50%. In valley regions, where weather conditions are more favourable to anaerobic digestion, women and children can save 80–90% of the time spent to firewood collection [6]. Nevertheless, our families declared that children and women can already spend more time for other activities.

The development and management of biogas technology are far from a purely technical question and almost always involve human behaviour characteristics and cultural aspects [44,45]. In fact, digesters are often defined as a "gender technology", because women are the most beneficiated by digesters implementation [5]. Saving time for firewood collection, as well as indoor environmental improvement, affects especially women. Women can use most of the saved time in recreation activities, social and communities' work, income generating activities and reading. This increases women education and participation [5,8] and contributes to community's development.

7. Conclusions

This study quantifies technical, environmental, economic and social benefits of low-cost tubular digesters implemented in rural communities of the Peruvian Andes. Although the potential benefits are restricted by the performance of biogas systems at high altitude, household digesters improve the living quality of rural families appreciably. In fact, biogas production covers around 60% of fuel needs for cooking, leading to 50–60% decrease in firewood consumption (i.e. deforestation) and greenhouse gases emissions; while the annual income is increased by 3–5.5% due to fertilizer saving and potato sale. These values could be improved by enhancing digesters performance and the sustainability of the technology.

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